AC Corrosion of Electrically Heated Pipelines

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ABSTRACT

A development program to further increase the competitiveness of the direct electrical heating technology has been initiated. By increasing the power frequency from 50/60 to 100-200 Hz, less current is needed to develop the same heat generation in the pipe. A test program is running with the purpose of studying AC corrosion on the cathodically protected steel pipelines at higher frequencies. This article presents results from initial tests, showing that corrosion on steel specimens are present at 60 Hz, but that zero or very little corrosion is present at 100 and 200 Hz. On the aluminum specimens, corrosion rate is reduced by 55 % from 60 to 100 Hz. and is somewhat further reduced at 200 Hz.

KEY WORDS: DEH; Direct Electrical Heating; AC Corrosion; Corrosion; Higher power frequency; Test program; Experiment.

INTRODUCTION

When a hydrocarbon production pipeline is shut down, it gradually cools to a temperature level where hydrates or wax may be formed. If hydrates and wax are formed in a pipeline, these may restrict the flow and may in a worst case situation block the entire pipe. Removal of hydrates is very difficult and potentially hazardous. One of the traditional methods for hydrate or wax prevention is to add chemical inhibitors to the well-stream. In continuous operation this method has considerable operational costs, (Hesjevik, 2006). Chemical treatment requires storage tanks, inhibitor regeneration plants, piping and pumps on the platform or vessel that occupy space and deadweight tonnage, as well as a sizeable subsea piping infrastructure. One of several alternative qualified methods to prevent hydrates and wax formation is direct electrical heating (DEH).

A 3-year development program for further increase of the competitiveness of the DEH technology was initiated in 2016. An innovative step by increasing the power frequency is proposed. Pre-studies indicate clear benefits by going from a DEH-system operating at normal power frequency of 50/60 Hz to a system operating at a frequency ranging between 100 and 200 Hz, (Lervik, 2016). In a DEH-system, electric alternating currents of some hundred amperes are transferred from the steel pipe to the surrounding seawater. Thus, AC corrosion aspects must be considered. At present, DEH systems are only qualified for use at 50 and 60 Hz power frequency. One of the outstanding issues is related to AC corrosion.

Empirical studies (French, 1973; Guo, 2015) show that AC corrosion on steel and aluminum specimens (without cathodic protection) decreases when increasing the power frequency. At frequencies greater than 100 Hz, the corrosion rate on steel is relatively unchanged, (Pagano, 1994). Though none of the above studies are directly applicable to DEH-systems, the same behavior is expected. The effects will be verified and quantified in the development program. The full test program examines AC corrosion of pipeline steel and anodes at various frequencies (50-200 Hz), temperatures, current densities etc. All tests are small-scale AC corrosion testing of steel (cathode) and aluminum (anode) in artificial seawater performed in a laboratory environment. This paper presents results from the initial tests, where the power frequency is varied.

DEH SYSTEM OVERVIEW

In a DEH-system, electric current is conducted by the flowline steel. Heat is generated due to the flowline resistance, keeping the well-stream above the critical temperature for hydrate formation. For safety and reliability reasons, the heating system is electrically connected ("earthed") to surrounding seawater through several sacrificial anodes. Typically, 40 % of the current is conducted by seawater while the flowline steel conducts the remaining 60 %, (Nysveen et al., 2007). This is indicated in Fig. 1.
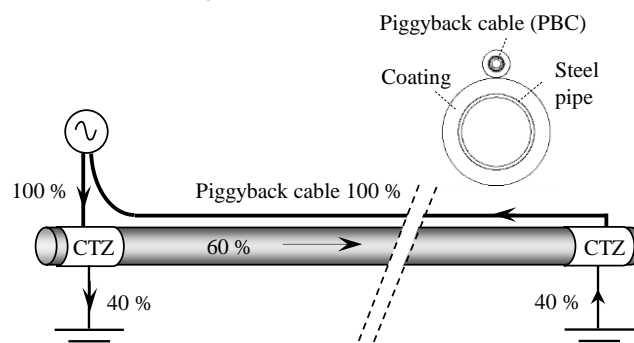

Fig. 1: Principle sketch of DEH. Percentages of applied current conducted by piggyback cable, steel pipe and seawater is indicated.

The region where most of the current leaves or enters the pipeline is defined as the current transfer zone (CTZ), (Lervik, 2004). The length of the current transfer zone has been determined with mathematical models and confirmed with full scale testing on an 8" diameter pipeline. The length was found to vary with the permeability of the pipeline steel, but ranges from 30 to 50 meters, (Hesjevik, 2006).

The first DEH-system was installed in the North Sea 17 years ago and today there are approx. 30 flowlines installed with this technology. In 2015, a DEH system was installed on a 13 inch and 43 km long flowline at depths exceeding 1000 m. The next planned DEH flowline on the Norwegian shelf is planned to be in operation by 2018.

DESIGN OF CORROSION PROTECTION SYSTEM

AC corrosion issues are handled by connecting aluminum anodes to the pipeline. Especially in the CTZ, the anodes are placed close, (Lervik, 2004). The anodes work as electrodes for the current transfer. In order to limit AC corrosion to acceptable levels, the current density on the anodes are often limited to 40 A/m^2. As an example, if 400 A were to be transferred from the pipe to sea, the total anode area exposed to sea should be at least 10 m^2

AC corrosion is most relevant in the
- CTZ,
- where pipeline steel is exposed to seawater (inline Tees, bypasses, coating damages etc.),
- in adjacent metallic structures (pipelines, service lines, instrument/power umbilicals etc.) due to induced voltages from the DEH-system

During the field developments, the acceptance limits have varied between 20 and 40 A/m^2 for aluminum and from 100 to 240 A/m^2 for carbon steel to keep corrosion at acceptable levels, (Lervik, 2004; Nysveen, 2007; personal communication).

EXPERIMENTAL METHOD

The steel and aluminum specimens were coin shaped with a thickness of 2 mm, see Fig 2. Exposed areas were 0.79 cm^2 and 3.84 cm^2, respectively. For steel, AC corrosion acceptance limits are typically referred to crack sizes of 1 cm^2, like in British Standard 15280. Thus, a steel specimen size of approx. 1 cm^2 is preferred. All specimens were chemically cleaned, dried and weighed before and after the tests. Steel specimen were cleaned by a mixture of concentrated hydrochloric acid (HCl), antimony trioxide (Sb$_2$O$_3$) and stannous chloride (SnCl$_2$), aluminum by concentrated nitric acid (NHO$_3$) and chrome oxide (CrO$_3$)

Fig 2: Aluminum (left) and steel specimen (right) before tests.

The specimens were placed in special-built containers, where only one side was exposed to seawater. See Fig. 3. An insulated electrical wire was terminated to the reverse side of the specimen.
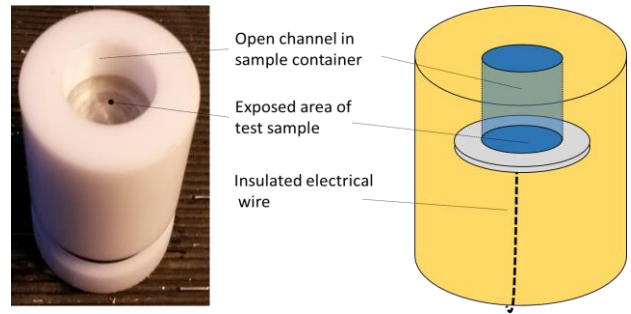

Fig 3: Container for steel specimen.

Each test consisted of three pairs of specimens located in storage boxes with a capacity of 10 L. The storage boxes were filled with approximately 8 L of tap water, mixed with 3.7 wt% sodium cloride.

An AC current was forced between pairs of specimens; one steel and one aluminum. One transformer was used for each pair to ensure equal amounts of current flowing in both specimens of each pair. Fig. 4 shows aluminum and steel specimens in the water filled box. The electrical system is indicated. The dotted purple lines show the current paths from one steel specimen to the corresponding aluminum specimen. Note that alternating current is applied. Thus, the current direction switches every 8.5 ms (60 Hz) to 2.5 ms (200 Hz).

The water was not stirred during the test period, only replenished as water vaporized. Ambient temperature was approx. 20℃.
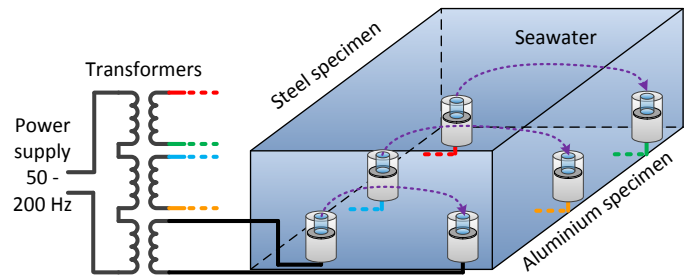

Fig. 4: Aluminum and steel specimens test setup. Electrical system is indicated. Dotted purple lines show the current path from one steel specimen to the corresponding aluminum specimen through seawater.

TEST PROGRAM

The full test program examines AC corrosion of pipeline steel protected by aluminum anodes at various frequencies (50-200 Hz), temperatures, current densities etc. The initial tests presented here examine how AC corrosion rate vary as a function of frequency at 60, 100 and 200 Hz. In addition, one set of reference specimens are connected to the transformers, without applying any power. See Table 1 for test program. The corrosion rate is calculated by using the weight loss method.

Table 1: DEH corrosion test program.

Test no.	Frequency [Hz]	Current density [A/m^2]		Comment	Object ID
		Steel	Aluminum		
1	-	0	0	Reference	A,B,C
2	60	127	26		D,E,F
3	100	127	26		K,L
4	200	127	26		M,O,P

All samples were placed in the seawater-filled boxes for about 28 days. The first 10 days, all samples were acclimatized, meaning that no AC current was applied. The final 18 days, AC current was applied to the test specimen, except for the reference group. AC current density of steel was 127 A/m^2, the aluminum 26 A/m^2.

RESULTS AND DISCUSSION

Corrosion rate on steel specimen

The resulting corrosion rates on the steel specimens are found to vary from -0.01 to 0.11 mm/year, see Fig. 5. The highest rate is found for specimen F, which was subjected to 60 Hz. The other two 60 Hz samples - E and D - show much lower rates, 0.2 and 0.3 mm/year. It is not known why the corrosion rate on sample F is significantly higher. All the other steel specimens - whether exposed 100 or 200 Hz, or not exposed to AC current at all (0 Hz) - are found to have corrosion rates in the -0.01 to 0.02 mm/year range.
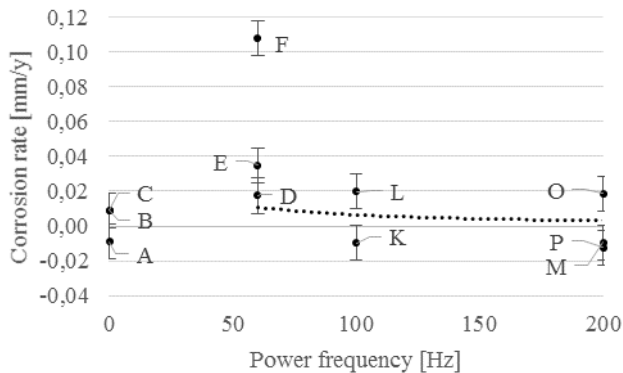

Fig 5: AC corrosion rate of steel specimens. Error bares indicate balance inaccuracy, which is one of the identified sources of error. The dotted line indicates the trend of the data.

Though the scatter is significant, the corrosion rates tend to decrease with increasing power frequency. This is indicated with a dotted line in Fig. 5. However, due to very little material loss of the specimens, the sources of error produce relatively large error margins. These error sources include the precision of the balance (0.2 mg) and the effectiveness of the cleaning process. Also, in some of the sample containers, evidence of moisture was detected inside the hull, possibly allowing for unintended corrosion on the reverse side of the samples. Evaluating the results in this light, the data suggest that all the non-60 Hz specimens have zero or very little corrosion, but that at 60 Hz some corrosion is present. Clearly, for carbon steel under cathodic protection (and no AC impressed) this is expected. It is promising with regards to increase power frequency of the DEH system that the samples exposed to AC current densities of 127 A/m^2 at 100 and 200 Hz show similarly low amount of corrosion.

Corrosion rate on aluminum specimen

The AC corrosion rate of aluminum varies between 0.3 and 1.0 mm/year, as shown in Fig. 6. The dotted line indicates the trend of the data. From 60 to 100 Hz, the corrosion rate decreases by approximately 55%. At 200 Hz the corrosion rate further decreases on two out of the three samples. However, on the third sample (P), a significantly higher corrosion rate is found. No explanation for this anomaly is identified. The error margins in these tests are much smaller than in the steel tests due to greater material loss, meaning that the accuracies of the balance and the cleaning process are of relatively
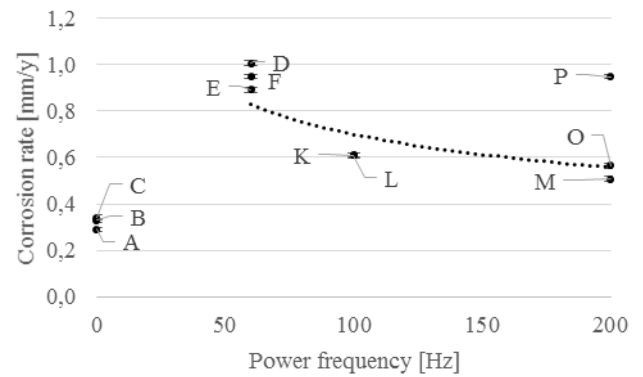
lower importance.

Fig 6: AC corrosion rate of aluminum specimens. Error bares indicate balance inaccuracy, which is one of the identified sources of error. The dotted line indicates the trend of the data, excluding sample P.

Unsurprisingly and in accordance with other studies, (Hesjevik, 2016), the general corrosion rates on the aluminum samples are greater than on the steel samples. Also again, there is a tendency that the corrosion rate decreases with increasing frequency. Interestingly, at 60 Hz the corrosion rate of ~1.0 mm/year is about three times larger than the no-AC case, suggesting that anodes exposed to this AC current density level are consumed thrice as fast as normal. At 100 Hz, the consumption is about twice the normal rate, and at 200 Hz, two of three samples indicate that the consumption is further reduced. In relation to DEH systems, a lower consumption rate means that the service time of the anodes is extended. Alternatively, at higher frequencies it may be possible to allow for larger AC current loads on each anode without drastically increasing consumption rate, resulting in fewer anodes in total and a simpler and cheaper system.

Images of aluminum and steel specimens after the corrosion tests and cleaning process are shown in Fig. 7. The steel specimen shows little or no corrosion. On the aluminum surface, several regions of pitting corrosion are found. Thus, on the aluminum surface, the corrosion rate in the pits is larger than the average rate calculated by the weight loss method.

Fig. 7: Aluminum (left) and steel (right) specimens after corrosion test and cleaning process.

Other findings

During testing, gas evolution was observed on the specimens that were exposed to AC currents. Gas evolution was found to be more prominent on the aluminum samples than on the steel samples, and seemed to decrease with higher frequencies. Fig. 8 shows bubbles forming above an aluminum sample exposed to 60 Hz.

Fig. 8: Gas evolution on aluminium specimen at 60 Hz.

The gas is most likely hydrogen (H_2) and develops due to reduction of water:

$$2H_2O + 2e^- \rightarrow H_2 \text{ (g)} + 2OH^- \tag{1}$$

This reaction is an alternative to the reduction of oxygen, and becomes significant when the electrode potential is reduced below -1.1 V (vs. Ag/AgCl). Thus, there is indication that the electrode potential drops below this level at least during parts of the AC cycle.

A reduction of the gas evolution at higher frequencies could be expected if modelling the metal-electrolyte interface layer using the Randles circuit, given in Fig. 9. The double layer resistance and capacitance are indicated by R and C. Only the currents flowing through the resistor represents electrochemical reactions, as the capacitor represents accumulation (charging) and dissipation (discharging) of charged particles. As the frequency increases, a larger share of the current is capacitive, reducing the current conducted through the resistance, and hence lessening the gas producing electrochemical reactions On a similar basis it can be argued that the lower gas evolution on the steel electrodes are due to most of the current transferred through the capacitor.
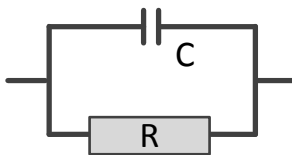

Fig. 9. Randles circuit of metal/electrolyte interface, indicating double layer capacitance (C) and resistance (R).

Hydrogen evolution is generally unwanted, as it is considered increasing the risk for hydrogen induced stress cracking (HISC). Increasing the power frequency to 100 – 200 Hz seems advantageous regarding reducing the hydrogen evolution, and consequently, mitigating the risk for HISC.

Input to further testing

Several lessons learned from the initial tests will be adopted to the remaining test program:

- More duplicates should be used in each experiment to ensure statistically better results.
- Specimen containers must be inspected to avoid water ingress.
- Cleaning process may be improved to remove any bi-products.
- Electric current for each test should be recorded to study any changes in impedance.
- Grid voltage variations should be recorded. This only applies when no fixed voltage instruments are used, like a frequency converter.
- Monitoring the electrode potential could provide useful information of the double layer and electrochemical reactions taking place on the surfaces.

CONCLUSIONS

For steels, impressing an AC current density of 127 A/m^2, zero or very little corrosion are found on the specimens exposed to 100 and 200 Hz, but some corrosion is present on the specimens exposed to 60 Hz. Reference tests without AC also show no corrosion.

At a current density of 26 A/m^2, the aluminum specimens exposed to 60 Hz show a corrosion rate of about three times larger than the no-AC case. At 100 and 200 Hz, the consumption is about twice the no-AC rate.

The results are promising with regards to increasing the power frequency on the DEH system.

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